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SESSION ID: CRYP-T01A

Simplified Adaptively Secure Threshold BLS Signatures

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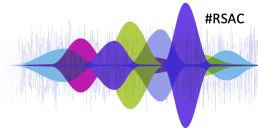
Zama, France

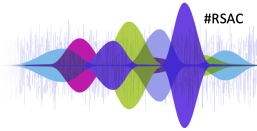
Outline



1. Threshold Cryptography
   - Motivation
   - Static vs Adaptive corruptions
   - Security Definition

2. Adaptively Secure Threshold BLS Signatures
   - The Das-Ren Scheme and its proof intuition
   - Our Simplified Scheme
   - Comparison

Threshold Cryptography



- Splitting secret keys among shareholders (`Desmedt-Frankel, Crypto'89; Boyd, IMA'89`):

  Enhances the security of highly sensitive keys and the availability of systems

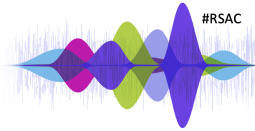
- **Motivation:** Avoid single points of failure

  - Attacks on certification authorities lead to fake certificates distributed over the Internet and destroy the "trust infrastructure"

    e.g., DigiNotar was hacked and attacker produced a DigiNotar-signed "Google certificate" (September 2011)

  - Also useful in blockchain applications

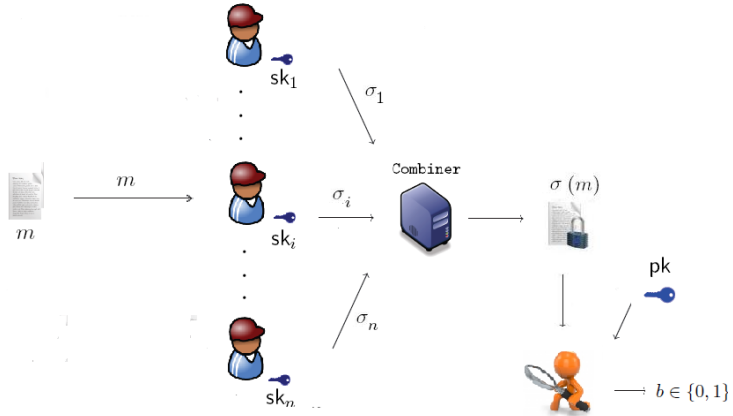
Threshold Cryptography

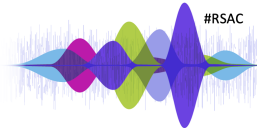


- Split private keys into n shares $SK_1, \ldots, SK_n$ so that knowing strictly less than $t + 1 < n$ shares is useless to the adversary
- Quorum of $t + 1 < n$ shareholders must contribute to private key operations
- Key generation is either centralized (trusted dealer) or distributed
- Useful properties:
  - Robustness: up to $t < n$ malicious servers cannot prevent an honest majority from decrypting/signing
  - Optimal resilience: robustness against any minority $t \leq (n - 1)/2$
  - Non-interactivity: no communication among shareholders
  - No reliance on reliable erasures

Threshold Cryptography

Non-interactive (t, n)-threshold signatures

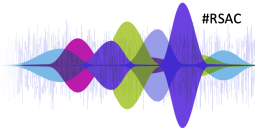




Static Corruptions

Adversary corrupts servers *before* seeing the public key

- First threshold signatures (non-exhaustive):
  - `Desmedt-Frankel (Crypto'91)`: threshold RSA w/o robustness
  - `De Santis` *et al.* `(STOC'94)`: provably secure, but large partial signatures
  - `Gennaro` *et al.* `(Eurocrypt'96 & Crypto'96)`: threshold DSA & RSA signatures



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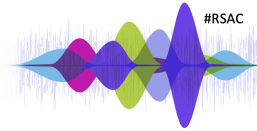
  - `Gennaro` *et al.* `(Eurocrypt'96 & Crypto'96)`: threshold DSA & RSA signatures
- Robust threshold signatures without interaction:
  - `Shoup (Eurocrypt'00)`: threshold RSA signatures
  - `Katz-Yung (Asiacrypt'02)`: threshold Rabin signatures
  - `Boldyreva (PKC'03)`: short threshold BLS signatures
  - `Boneh` *et al.* `(Crypto'18)`: universal thresholdizers



Adaptive Corruptions

Adversary corrupts up to t servers *at any time*

- With interaction (non-exhaustive)
  - Assuming erasures
    (Canetti *et al.*, Crypto'99; Frankel-MacKenzie-Yung, ESA'99, Asiacrypt'99)
  - Without erasures (Jarecki-Lysyanskaya, Eurocrypt'00; Abe-Fehr, Crypto'04)
  - Optimal resilience, better efficiency (Bacho *et al.*, Eurocrypt'24)
- Without interaction
  - Short signatures (2 group elements) without interaction, erasures, or trusted dealer
    (Libert-Joye-Yung, PODC'14)
  - Adaptive security in the AGM for threshold BLS (Bacho-Loss, CCS'22)
  - Optimally short threshold BLS in the ROM (Das-Ren, Crypto'24)

Our Contribution

- A simpler version of the Das-Ren threshold BLS signature:
  - Shorter secret key shares (2 elements of $\mathbb{Z}_p$ instead of 3)
  - Shorter partial signatures (by $\approx 20\%$)
  - Faster partial signing (by $\approx 25\%$) and verification (by $\approx 33\%$)
  - Smaller verification keys (by $\approx 50\%$)
  - Smaller communication in distributed key generation (by $\approx 50\%$)
- …while retaining advantages
  - Adaptive security without erasures; no interaction among signers
  - Optimal-size signatures
  - One-round DKG

Non-interactive Threshold Signatures

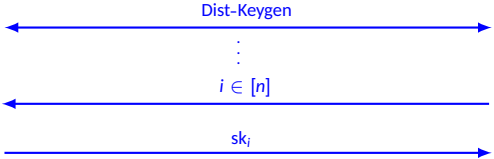
Security under chosen-message attacks:

Dist-Keygen

$\{sk_i\}_{i \in C}$, pk

Non-interactive Threshold Signatures

Security under chosen-message attacks:



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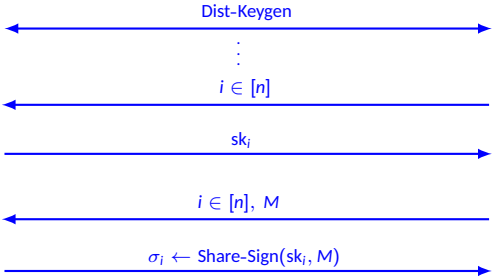

$\{\mathsf{sk}_i\}_{i \in \mathcal{C}},\ \mathsf{pk}$

Non-interactive Threshold Signatures

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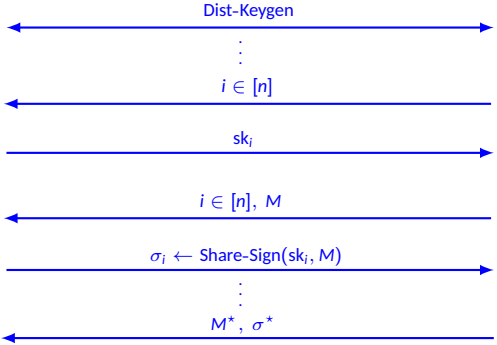
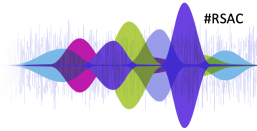


$\{\mathsf{sk}_i\}_{i \in \mathcal{C}},\ \mathsf{pk}$

Adversary wins if:

- $\text{Verify}(\mathsf{pk}, M^\star, \sigma^\star) = 1$
- $|\mathcal{V} \cup \mathcal{C}| \leq t$ where $\mathcal{V} := \{i \in \{1, \ldots, n\} \mid (i, M^\star) \text{ was queried}\}$

BLS Signatures (Boneh-Lynn-Shacham, Asiacrypt'01)



- Based on bilinear maps $e : \mathbb{G} \times \hat{\mathbb{G}} \to \mathbb{G}_T$ s.t.

$$e(g^a, \hat{h}^b) = e(g^b, \hat{h}^a) = e(g, \hat{h})^{ab} \qquad \forall g \in \mathbb{G},\ \hat{h} \in \hat{\mathbb{G}},\ a, b \in \mathbb{Z}$$

- Uses a random oracle $H : \{0,1\}^* \to \mathbb{G}$; Public key is $\hat{g}^s$
- Signature is

$$\sigma = H(M)^s \in \mathbb{G}$$

- Verification checks if $e(\sigma, \hat{g}) = e(H(M), \hat{g}^s)$
- Easy to thresholdize (Boldyreva, PKC'03): optimal-size secret-key shares, static security

Hardness Assumptions

The **Decision Diffie-Hellman (DDH)** problem

In pairing-frienly groups $(\mathbb{G}, \hat{\mathbb{G}}, \mathbb{G}_T)$ of prime order p: distinguish between

$$\left\{ \left(g,\ g^a,\ g^b,\ g^{ab}\right) \in \mathbb{G}^4 \mid a, b \xleftarrow{R} \mathbb{Z}_p \right\}, \quad \left\{ \left(g,\ g^a,\ g^b,\ g^c\right) \in \mathbb{G}^4 \mid a, b, c \xleftarrow{R} \mathbb{Z}_p \right\}$$

The **co-Diffie-Hellman (co-CDH)** problem

In pairing-frienly groups $(\mathbb{G}, \hat{\mathbb{G}}, \mathbb{G}_T)$: given

$$\left(g,\ g^a,\ g^b\right) \in \mathbb{G}^3, \qquad \left(\hat{g},\ \hat{g}^a\right) \in \hat{\mathbb{G}}^2$$

with $a, b \xleftarrow{R} \mathbb{Z}_p$, find $g^{ab} \in \mathbb{G}$

The Das-Ren Scheme

- Public key is

$$\mathsf{pk} = \left(\hat{g},\ \hat{h},\ \hat{v},\ \hat{g}^{s} \right) \in \hat{\mathbb{G}}^4$$

- $s \in \mathbb{Z}_p$ is shared as $\{ \mathsf{sk}_i = (s(i), r(i), u(i)) \}_{i \in [n]}$ via

$$s[X] = s + s_1 X + \cdots + s_t X^t, \qquad r[X] = 0 + r_1 X + \cdots + r_t X^t, \qquad u[X] = 0 + u_1 X + \cdots + u_t X^t$$

Verification keys are $\left\{ \mathsf{vk}_i = \hat{g}^{s(i)} \cdot \hat{h}^{r(i)} \cdot \hat{v}^{u(i)} \in \hat{\mathbb{G}} \right\}_{i \in [n]}$

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- Partial signatures $\sigma_i = H_0(M)^{s(i)} \cdot H_1(M)^{r(i)}$ are proven consistent with vk_i

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- Partial signatures $\sigma_i = H_0(M)^{s(i)} \cdot H_1(M)^{r(i)}$ are proven consistent with vk_i
- For any $(t+1)$-set $S \subset [n]$,

$$\sigma = \prod_{i \in S} \sigma_i^{\Delta_{i,S}(0)} = H_0(M)^s$$

Adaptive Security: Intuition

Theorem (Das-Ren, Crypto'24)

In the ROM, the fully distributed scheme is adaptively secure for any $t \leq (n-1)/2$ *under the co-CDH assumption in* $(\mathbb{G}, \hat{\mathbb{G}})$ *and the DDH assumption in* $\mathbb{G}$

Proof intuition:

- Make partial signatures $\sigma_i = H_0(M)^{s(i)} \cdot H_1(M)^{r(i)}$ information-theoretically hide $s(i)$

  Move to a game where $\{(H_0(M), H_1(M))\}_{M \neq M^\star}$ live in a 1-dimension subspace (using DDH in $\mathbb{G}$)

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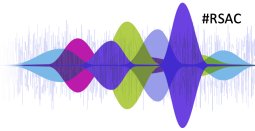
- Switch to $r[X]$ s.t. $r(0) = 1$ for a "rigged"

$$\mathsf{pk} = \hat{g}^{s(0)} \cdot \hat{h}^{r(0)} = \hat{g}^{s(0)+a}$$

  Forgery $\sigma^\star = H_0(M^\star)^{s(0)+a}$ reveals co-CDH solution g^{ab} if $H_0(M^\star) = g^b$

Adaptive Security: Intuition



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- **Difficulty:** Hide the replacement of $r(0) = 0$ by $r(0) = 1$
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- **Our solution**: Make the information revealed by vk_i redundant with $\sigma_i = H_0(M)^{s(i)} \cdot H_1(M)^{r(i)}$
  - Verification keys are $\mathsf{vk}_i = g^{s(i)} \cdot h^{r(i)}$ (live in $\mathbb{G}$ instead of $\hat{\mathbb{G}}$)
  - Make $\{(H_0(M), H_1(M))\}_{M \neq M^\star}$ colinear with $(g, h) \in \mathbb{G}^2$ using DDH

Our Simplified Scheme

- Public key is

$$\mathsf{pk} = \left((g,\ h) \in \mathbb{G}^2,\ (\hat{g},\ \hat{g}^s) \in \hat{\mathbb{G}}^2 \right)$$

- $s \in \mathbb{Z}_p$ is shared as $\{ \mathsf{sk}_i = (s(i), r(i)) \}_{i \in [n]}$ using

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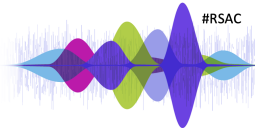

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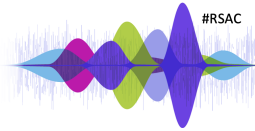

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- Partial signatures $\sigma_i = H_0(M)^{s(i)} \cdot H_1(M)^{r(i)}$ are proven consistent with vk_i

- For any authorized set $S \subset [n]$, we get $\sigma = \prod_{i \in S} \sigma_i^{\Delta_{i,S}(0)} = H_0(M)^s$

Security

Theorem

In the ROM, the fully distributed scheme is adaptively secure for any $t \leq (n-1)/2$ under the co-CDH assumption in $(\mathbb{G}, \hat{\mathbb{G}})$ and the DDH assumption in $\mathbb{G}$

Proof idea:

- (Modified) DKG protocol only uses $g, h = g^a \in \mathbb{G}$; $\hat{g}^a$ is *not* public
- Choose a random $i^\star \in [n]$ that won't be corrupted (with probability $> 1/2$)
  (`Frankel-MacKenzie-Yung, ESA'99`; `Canetti et al., Crypto'99`)
- Use DDH to make $\{(H_0(M), H_1(M))\}_{M \neq M^\star}$ colinear with $(g, h) \in \mathbb{G}^2$
- "Program" $r[X]$ to have $r(0) = 1$ by making player $i^\star \in [n]$ share $r_{i^\star}(0) = 1$ in the DKG
- Prove that an adversary corrupting $\leq t$ players cannot detect the switch

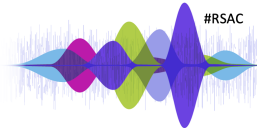
Comparison

	Assumptions	$\lvert\{\mathsf{vk}_i\}_{i=1}^n\rvert$	$\lvert\mathsf{sk}_i\rvert$	$\lvert\sigma_i\rvert$	Partial signing cost	Partial verification cost
Boldyreva*	co-CDH	$n \times \lvert\hat{\mathbb{G}}\rvert$	$1 \times \lvert\mathbb{Z}_p\rvert$	$1 \times \lvert\mathbb{G}\rvert$	1 $\mathsf{exp}_{\mathbb{G}}$	2 pairings
Das-Ren	co-CDH + $\mathsf{DDH}_{\mathbb{G}}$	$n \times \lvert\hat{\mathbb{G}}\rvert$	$3 \times \lvert\mathbb{Z}_p\rvert$	$1 \times \lvert\mathbb{G}\rvert + 4 \times \lvert\mathbb{Z}_p\rvert$	4 $\mathsf{exp}_{\mathbb{G}}$ + 3 $\mathsf{exp}_{\hat{\mathbb{G}}}$	3 $\mathsf{exp}_{\mathbb{G}}$ + 4 $\mathsf{exp}_{\hat{\mathbb{G}}}$
Our scheme	co-CDH + $\mathsf{DDH}_{\mathbb{G}}$	$n \times \lvert\mathbb{G}\rvert$	$2 \times \lvert\mathbb{Z}_p\rvert$	$1 \times \lvert\mathbb{G}\rvert + 3 \times \lvert\mathbb{Z}_p\rvert$	6 $\mathsf{exp}_{\mathbb{G}}$	6 $\mathsf{exp}_{\mathbb{G}}$

Figure: Comparison among non-interactive threshold BLS signatures

∗ Only proven secure under static corruptions in the ROM

- Our DKG decreases the broadcast channel communication by a factor 2
  Each player only sends t elements of $\mathbb{G}$ (instead of $\hat{\mathbb{G}}$)
- Like [DR24], we only need DDH in the proof of adaptive security



Summary

- Simplification of the Das-Ren threshold BLS signature which preserves
  - Adaptive security in the ROM, optimally short signatures
  - Non-interactive signing, no erasures, one-round DKG, robustness (under DDH assumption)
- Advantages:
  - Shorter private key shares (only *two* elements of $\mathbb{Z}_p$)
  - Smaller partial signatures, verification keys and communication in the DKG
- Extensions
  - Adaptively secure Naor-Pinkas-Reingold distributed PRFs (`Eurocrypt'99`)
  - Adaptively secure distributed VRFs in the ROM

Questions?

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SESSION ID: CRYP-T01B

DSKE: Digital Signatures with Key Extraction

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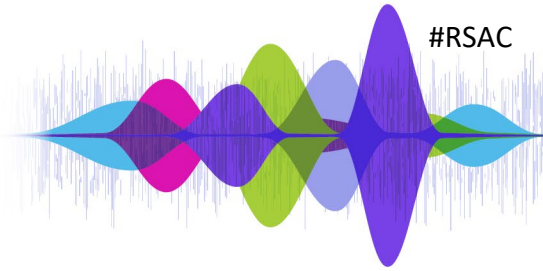

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Motivation: Long-lived Signature

Current Reality: Digital signatures provide authentication that remains valid indefinitely

Key Issue:

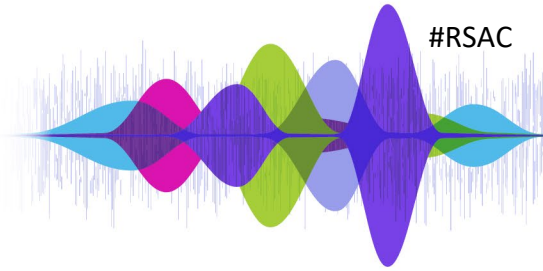
This "long-lived" property creates permanent records that can't be denied

Real-World Impact:

Legal evidence of authorship in many jurisdictions

Privacy concerns when signatures are attached to sensitive communications

Problem: The Spam Problem



- **Long-lived Signatures Enable Spam**: Current digital signature schemes have no built-in rate limiting
  - Spammers can create unlimited valid signatures with a single key
  - No effective cryptographic penalty for misuse
- **Current Anti-spam Solutions**:
  - Rely on centralized reputation systems or filtering
  - Lack cryptographic enforcement mechanisms
  - Challenge: How to limit signature creation while preserving authenticity?

Current Solutions

Off-the-Record (OTR) Communication:

Requires interactive key agreement before messaging

Not scalable for applications like email with no prior interaction

Works for small-scale, synchronous communication only

Key Rotation Approaches:

Periodic publishing of old keys (e.g., DKIM solution)

Logistical challenges in key distribution

Reliance on trusted parties or external services

Continuous maintenance overhead

Research Questions

Key Challenge:

- Can we design signatures that: Provide immediate verification
- Allow later deniability without continuous key publishing
- Penalize excessive signature creation (spam prevention)
- Function without additional infrastructure

Our Approach: DSKE - addressing both deniability and spam prevention through controlled key extraction

DSKE: Definition and Properties

A DSKE consists of 4 algorithms $(Gen, Sign, Vrfy, Extract)$:

1. A key-generation algorithm Gen takes as input a security parameter 1^n and outputs a pair of keys *(pk, sk)* :
$$Gen(1^n) \rightarrow (sk, pk)$$

2. A signing algorithm takes as input a private key *sk* and a message *m* from some message space. It outputs a signature σ :
$$Sign(sk, m) \rightarrow \sigma$$

3. A verification algorithm *Vrfy* takes as input a public key *pk*, a message *m*, and a signature σ. It outputs a bit *b.*
$$\mathrm{Vrfy}(\mathrm{pk}, \mathrm{m}, \sigma) \rightarrow \mathrm{b} \in \{0,1\}$$

4. An extraction algorithm $Extract$ takes as : The extraction algorithm is a deterministic algorithm that takes as input a set of k distinct valid message-signature pairs (m_i, σ_i) sampled from some distribution, and outputs the underlying private key sk or $\perp$.
$$Extract(\{m_i, \sigma_i\}_{i \in [k]}, pk)$$

Properties

Existential Unforgeability

Extractability under Trusted Generation (useful for deniability)

Extractability under Untrusted Generation (useful for spam prevention)

Extractability with Trusted Generation

Definition 9 (Extractability with Trusted Generation). *A digital signature scheme has a (k, δ)-extractable set when the algorithm* Extract$(\cdot)$ *on input k distinct message-signature pairs $\{(m_i, \sigma_i)\}_{i\in[k]}$ and the public key pk, such that each σ_i is a valid signature on m_i under pk, outputs the private key sk with probability δ. That is:*

$$\Pr\left[\begin{array}{l} par \leftarrow \mathsf{Setup}(1^\lambda), (pk, sk) \leftarrow \mathsf{KeyGen}(par), \\ m_i \leftarrow \mathcal{M}, \ s.t. \ m_i \neq m_j, \ for \ i, j \in [k], i \neq j, \\ \sigma_i \leftarrow \mathsf{Sign}(sk, m_i), \\ sk' \leftarrow \mathsf{Extract}\left(\{(m_i, \sigma_i)\}_{i\in[k]}, pk\right) \end{array} : pk = \mathsf{extractPK}(sk')\right] = \delta$$

Extractability with Untrusted Generation

Definition 10 (Extractability with Untrusted Generation). *A digital signature scheme has a (k, δ)-extractable set when the algorithm* Extract$(\cdot)$ *on input k distinct message-signature pairs $\{(m_i, \sigma_i)\}_{i\in[k]}$ and the public key pk generated by an adversary $\mathcal{A}$, outputs the private key sk with probability δ:*

$$\Pr\left[\begin{array}{l} par \leftarrow \mathsf{Setup}(1^\lambda), (pk, \{(m_i, \sigma_i)\}_{i\in[k]}) \leftarrow \mathcal{A}(1^\lambda, par), \\ s.t.\ \mathsf{Verify}(pk, m_i, \sigma_i) = 1, \\ m_i \neq m_j,\ for\ i, j \in [k], i \neq j, \\ sk' \leftarrow \mathsf{Extract}\left(\{(m_i, \sigma_i)\}_{i\in[k]}, pk\right) \end{array} : pk = \mathsf{extractPK}(sk')\right] = \delta$$

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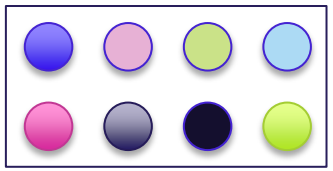
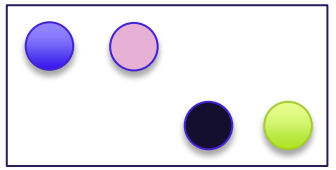
Constructions From Hash-based Signature

- **General Approach:** One-time/Few-time Hash-based signatures are those signature schemes that partially reveal the private key upon signing.

Lamport OTS

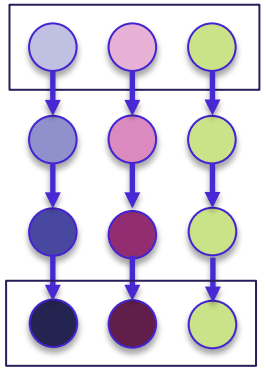


sk

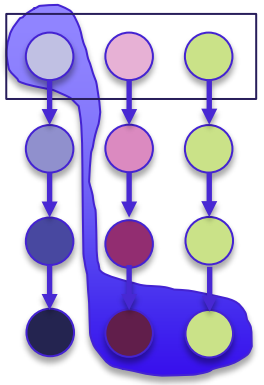


σ on 0011

Winterniz OTS



σ on 0011



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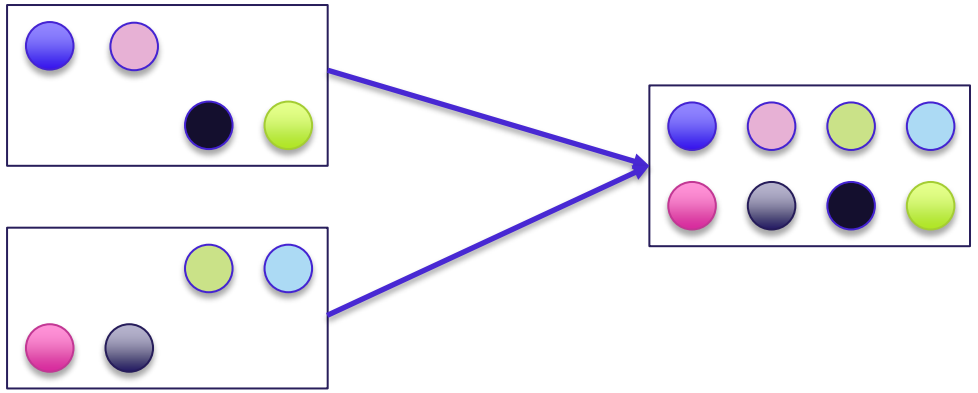
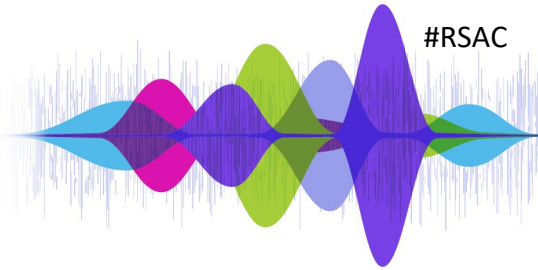
Constructions From Hash-based Signature

- Idea: With enough signatures on different message, one should be able to extract the key.



- Define Leakage function captures private key exposure from signatures
- Multiple signatures collectively provide enough information to reconstruct the full key
- Framework applies to most one-time/few time signature schemes (Biba, Winternizt) and provide the extraction probability

Limitation of Hash-based Signatures

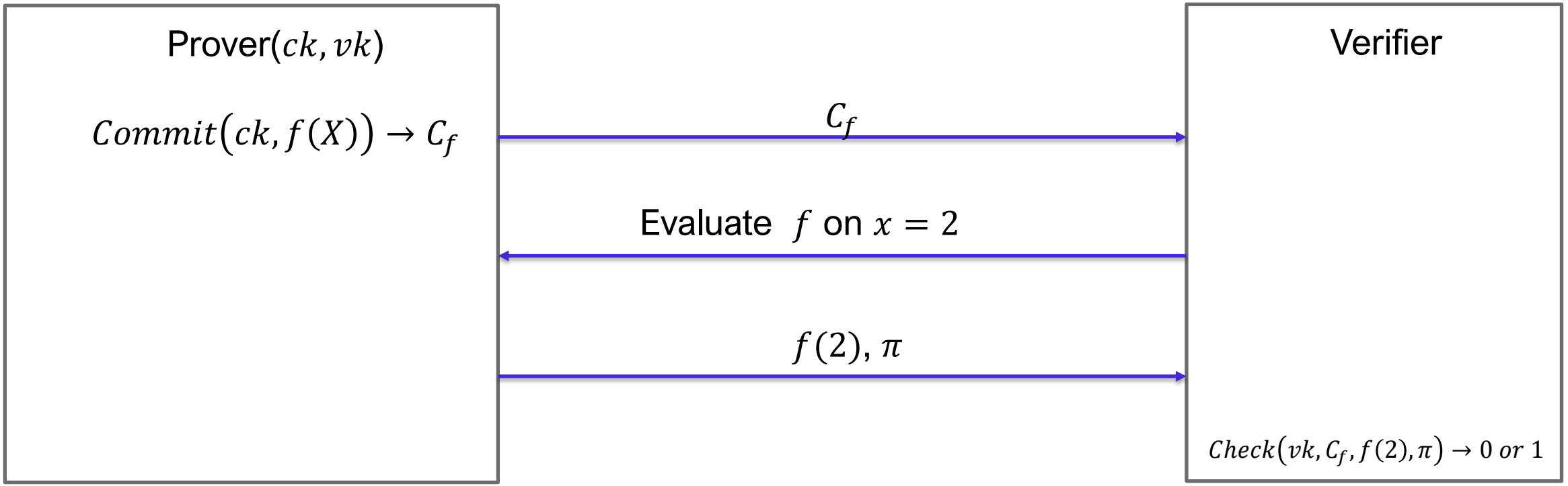


- Hash-based signatures have large signature sizes
- Do not satisfy extraction under untrusted generation

Polynomial Commitment-based DSKE

- Polynomial Commitment introduced by Kate, Zaverucha, and Goldberg

$$Setup(1^{\lambda}) \rightarrow ck, vk$$



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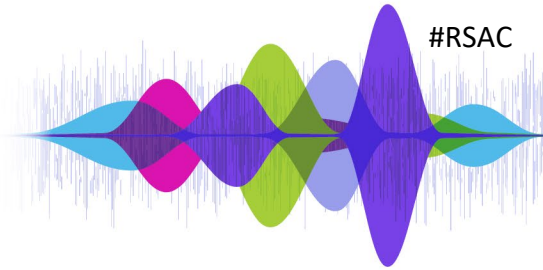
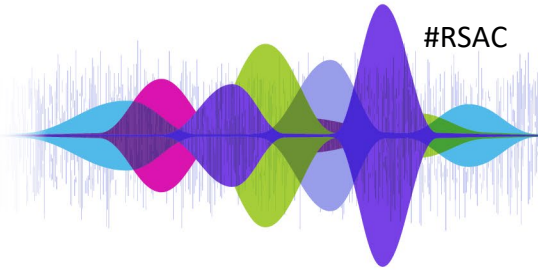
Compile Polycommit into Digital Signature



- Use Fiat-Shamir Transformation.
- Idea:
  - Private key: Polynomial $f(X)$ of degree d
  - Public key: Commitment to polynomial com_f
  - Signature: Evaluation of $f(X)$ at $H(message)$ along with the polycommit proof, π
  - Key extraction: Any $d+1$ valid signatures reveal $f(X)$ via Lagrange interpolation
- We formally proved that this construction satisfies unforgeability, extraction under both trusted and untrusted generations.

Advantages of PolyCommit Based DSKE



- **Practical Benefits**:
  - Shorter signature size
  - Deterministic extraction (100% success rate)
  - Signer can set exact threshold $(d + 1)$
  - Supports untrusted generation
  - Resists manipulation attempts

Application: GroupForge

- **Problem Addressed**: Email deniability without publishing old keys
- **GroupForge Construction**:
  - Builds on DSKE with Merkle trees
  - Time-chunk based approach like KeyForge [USENIX Sec ’21]
  - Key difference: No publishing of expired keys needed
  - Deniability emerges from extractable sets

Application: GroupForge

DSKE+Merkle Tree

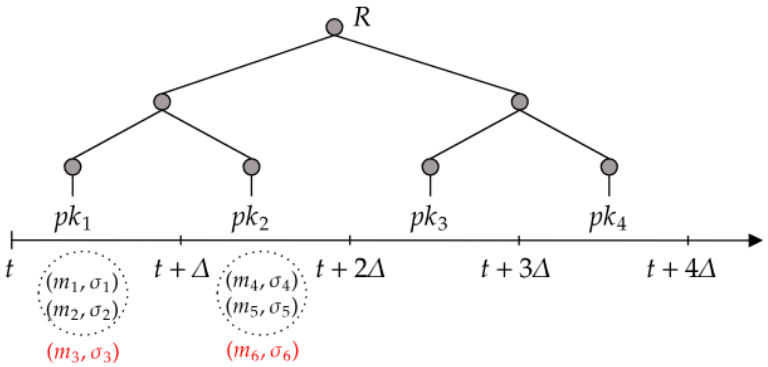


Figure 2: An example of GroupForge for $h_T = 2$ and between the interval $[t, t+2^{h_T} \cdot \Delta]$. In this example, $\{(m_i, \sigma_i)\}_{i\in[2]}$ can potentially act as the deniable group (see Section 8 for detailed discussions) for the message-signature pair (m_3, σ_3), and $\{(m_i, \sigma_i)\}_{i\in\{4,5\}}$ can act as the deniable group for the message-signature pair (m_6, σ_6).

More Efficient Construction

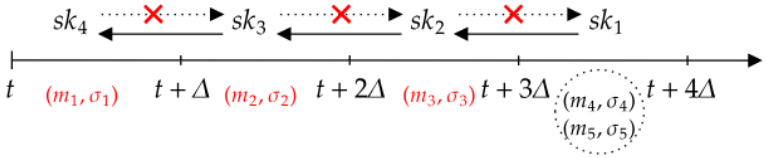


Figure 3: An example of GroupForge using FSS. The group $\{(m_i, \sigma_i)\}_{i\in\{4,5\}}$ can act as a deniable group that can reconstruct the private key to deny all message-signature pairs in the past, $\{(m_i, \sigma_i)\}_{i\in[3]}$.

GroupForge vs. Alternatives

Comparative Advantages: No reliance on continuous key publishing (unlike KeyForge)

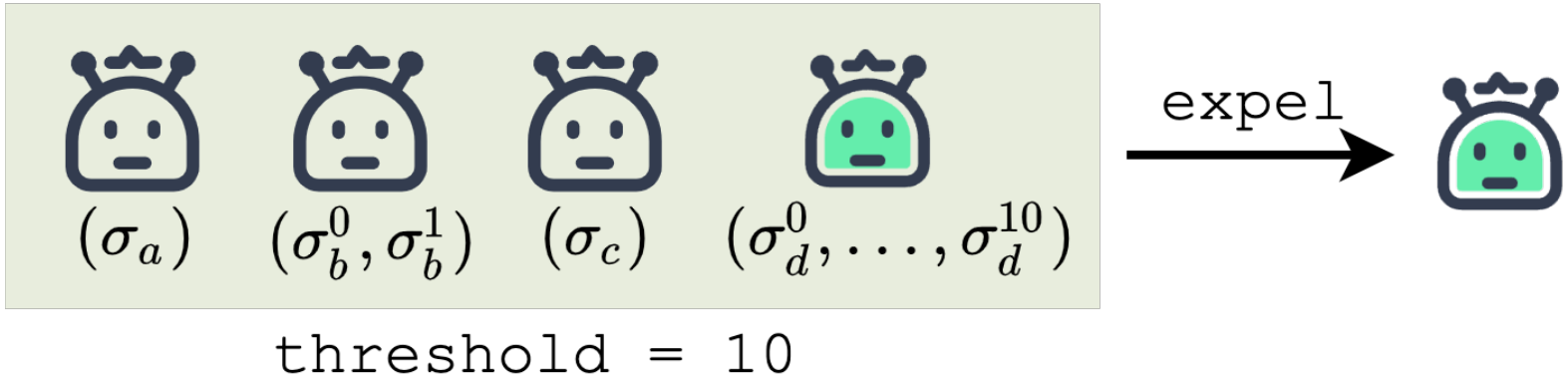
No dependence on external services (unlike TimeForge)

No need for VDFs or other expensive cryptography

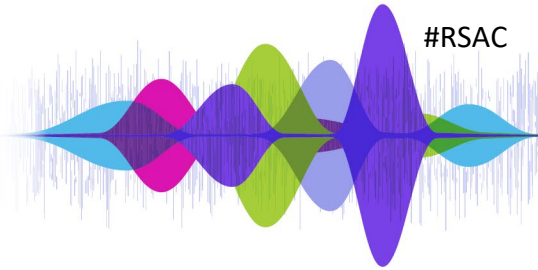
Functions as both forward-forgeable signature and short-lived signature

Application: Rate-Limiting Nullifier

- **Direct Application: Spam Prevention Mechanism**:
  - Uses key extraction as penalty for overuse
  - Private key exposure after threshold actions
  - System expels users who exceed their allocation



Anonymous RLN Extensions



- **Privacy Considerations**:
  - DSKE can be combined with NIZK to hide public keys
  - Challenge: Collecting extractable set while preserving anonymity
  - Linkable anonymity as middle ground
  - Future research direction

Implementation and Performance

Table 1: Performance of $\mathsf{DSKE}_{\mathsf{lamp}}$ and $\mathsf{DSKE}_{\mathsf{kzg}}$. Note that the probability of extracting the key in $\mathsf{DSKE}_{\mathsf{lamp}}$ is overwhelming in k, so the actual size of the extractable group can be smaller than $k = 64$.

Scheme	Group Size	Key Generation	Signing	Verification	Extraction
$\mathsf{DSKE}_{\mathsf{lamp}}$(SHA256)	$k = 64$	$451.583\mu s$	$17.625\mu s$	$160.458\mu s$	$45.083\mu s$
$\mathsf{DSKE}_{\mathsf{kzg}}$(BLS12-377)	$k = 16$	$2.795ms$	$2.425ms$	$4.949ms$	$1.785ms$
	$k = 32$	$2.825ms$	$2.523ms$	$6.123ms$	$7.813ms$
	$k = 64$	$2.852ms$	$2.756ms$	$7.202ms$	$35.341ms$
	$k = 128$	$3.624ms$	$3.404ms$	$8.045ms$	$166.433ms$

Table 2: Performance of GroupForge Constructions with $\Delta = 0.5$ hour.

Scheme	Parameters: Tree height (Duration)	Key Generation	Signing	Verification
$\mathsf{GroupForge}_{\mathsf{hash}}$ (SHA256)	$h_T = 14$ (0.93 years)	$7.407s$	$21.791\mu s$	$176.541\mu s$
	$h_T = 15$ (1.87 years)	$14.815s$	$34.708\mu s$	$177.416\mu s$
	$h_T = 16$ (3.74 years)	$29.631s$	$41.291\mu s$	$178.083\mu s$
	$h_T = 17$ (7.48 years)	$59.262s$	$45.916\mu s$	$179.374\mu s$
$\mathsf{GroupForge}_{\mathsf{kzg}}$ (SHA256, BLS12-377, $k = 32$)	$h_T = 14$ (0.93 years)	$46.294s$	$1.554ms$	$6.139ms$
	$h_T = 15$ (1.87 years)	$92.588s$	$1.591ms$	$6.140ms$
	$h_T = 16$ (3.74 years)	$185.175s$	$1.611ms$	$6.141ms$
	$h_T = 17$ (7.48 years)	$370.350s$	$1.722ms$	$6.143ms$

Conclusion and Future Work

- **Contribution Summary:**
  - DSKE primitive reconciling verification and deniability
  - Multiple constructions with security proofs
  - Practical applications in email deniability and spam prevention
- **Future Direction:**
  - Multi-Signature Extensions
  - Addition Applications in Voting, Donations

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Many Voices.
One Community.

Thank You

Full Paper:

https://dl.acm.org/doi/10.1007/978-3-031-88661-4_7